RI 9582

REPORT OF INVESTIGATIONS/1995

In Situ Stress at the Lucky Friday Mine

(In Four Parts):

4. Characterization of Mine In Situ Stress Field

UNITED STATES DEPARTMENT OF THE INTERIOR

UNITED STATES BUREAU OF MINES

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UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

BUREAU OF MINES
Rhea Lydia Graham, Director

International Standard Serial Number
ISSN 1066-5552

CONTENTS

ILLUSTRATIONS

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

Metric Units

cm	centimeter	m	meter
GPa	gigapascal	MPa	megapascal
km	kilometer	pct	percent
kPa/m	kilopascal per meter		

U.S. Customary Units

ft	foot	psi	pound per square inch
in	inch	psi/ft	pound per squatre inch per foot

IN SITU STRESS AT THE LUCKY FRIDAY MINE

(In Four Parts):

4. Characterization of Mine In Situ Stress Field

By J. K. Whyatt,[1] T. J. Williams,[1] and W. Blake[2]

ABSTRACT

Researchers at the U.S. Bureau of Mines collected and analyzed overcore measurements and other indicators of in situ stress characteristics at the Lucky Friday Mine, Mullan, ID. An analysis of these data revealed that significant local variations in in situ stress are present in this mine and that these variations existed prior to mining. High stresses were found to be associated with the most competent strata and a locked section of a fault. An estimate of the predominant stress field was developed for mine-wide modeling. The estimate shows that the greatest principal stress was oriented north of northwest. This information should provide a basis for mine-wide structural modeling of the Lucky Friday Mine and should generate important insights into localized stress conditions, which may significantly affect both local and mine-to-mine variations in seismicity induced by excavation.

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INTRODUCTION

As part of the U.S. Bureau of Mines' (USBM's) ongoing research to reduce ground control hazards in deep metal mines, USBM researchers undertook the study described in this Report of Investigations (RI) to increase basic knowledge of the in situ stress field in the lower portion of the Lucky Friday Mine, Mullan, ID. This knowledge was sought to support ongoing applied research projects at the Lucky Friday Mine in the Coeur d'Alene Mining District of northern Idaho (figure 1). In particular, stress in the lower portion of the mine was of great interest to investigations of intensive rock bursting in this area. Sprenke and others (1991) estimated that the Lucky Friday Mine experiences a rock burst of magnitude 2.5 or greater on the average of once every 15 weeks. Knowledge of in situ stress is also important to research on new mining methods for deep mines (for example, the Lucky Friday underhand longwall experimental stope) (Whyatt and others, 1992).

Geomechanical engineering practice generally begins with an estimate of the in situ stress state of the rock before an opening is excavated. The stress state before and after excavation is one of the most widely estimated, calculated, and analyzed parameters in modern rock mechanics. Yet direct measurements of stress are few and far between because of the expense of current methods.

This series of RI's started with a reexamination of an overcore stress measurement (hereafter known as LF 4250) from the Lucky Friday Mine's 4250 level (Whyatt and Beus, 1995). The second RI covered a stress measurement (LF 5300) conducted by USBM researchers on the 5300 level of the mine (Whyatt and others, 1995b). The third RI reexamined a stress measurement (Star 7300) from the 7300 level of the nearby Star Mine (Whyatt and others, 1995a). The results of these measurements are summarized in table 1 as principal stresses and in table 2 as stress components in map coordinates.

The most recent of the three measurements, LF 5300, found unusually high stresses and a stress rotation that confused the stress picture. The nationwide collection of stress measurements compiled by Zoback and Zoback (1980; 1989) failed to provide much clarification because their data set did not include any of the overcore measurements that have been conducted in the Coeur d'Alene Mining District. In an effort to clarify these results, information was sought from other sources, including geologic studies and mining experience, that would provide some insight into the orientation and magnitude of stresses among overcore measurement sites. This fourth and final RI in the series synthesizes these overcore stress measurements with geologic and ground control information to form an improved picture of the in situ stress state at the Lucky Friday Mine.

Table 1.—Principal in situ stresses measured at sites in Lucky Friday and Star Mines

Stress component	Magnitude, MPa	Magnitude, psi	Bearing	Plunge
LF 4250 level:				
σ_1	91	13,200	N 40° W	13°
σ_2	55	7,900	S 41° W	33°
σ_3	37	5,400	N 68° E	54°
LF 5300 level:				
σ_1	135	19,600	S 80° W	34°
σ_2	73	10,500	N 4° W	9°
σ_3	69	10,000	S 81° E	54°
Star 7300 level:				
σ_1	54	7,800	N 38° W	10°
σ_2	42	6,000	N 74° E	66°
σ_3	34	4,900	S 48° W	22°

Table 2.—In situ stress magnitudes in map coordinates and estimated overburden pressures measured at sites in Lucky Friday and Star Mines

	LF 4250 level		LF 5300 level		Star 7300 level	
Stress component, MPa (psi):						
σ_{ns}	74	(10,700)	74	(10,700)	46	(6,700)
σ_{ew}	64	(9,200)	113	(16,400)	42	(6,100)
σ_v	45	(6,600)	90	(13,100)	42	(5,900)
$\tau_{ns/ew}$	-19	(-2,700)	7	(1,100)	-9	(-1,300)
$\tau_{ns/v}$	3	(400)	-5	(-700)	3	(500)
$\tau_{ew/v}$	-13	(-1,900)	-38	(-4,400)	1	(100)
Elevation, m (ft)	-270	(-885)	-590	(-1,935)	-471	(-1,544)
Depth, m (ft)	1,295	(4,250)	1,615	(5,300)	2,237	(7,340)
σ_v depth, MPa (psi)	35	(5,000)	43	(6,300)	60	(8,700)
σ_v model, MPa (psi)	40	(5,750)	49	(7,130)	55	(7,990)

GEOLOGY

The geology of the Coeur d'Alene Mining District, including the Lucky Friday Mine, is complex. The literature is incomplete and often contradictory on important points. However, there is sufficient information available to provide a general description of the geologic structures and stress regime that dominate the district. This section explores the geology of the district with implications for the predominate stress state on mine and local (mine opening) scales.

COEUR D'ALENE MINING DISTRICT FRAMEWORK

The Coeur d'Alene Mining District lies within late Precambrian sedimentary rocks of the Belt Supergroup. These rocks are exposed primarily in western Montana, northern Idaho, and southern British Columbia, where they define the Belt terrane. The Coeur d'Alene district lies within the west-central part of the basin, where it is intersected by the Lewis and Clark line (figure 1). The Lewis and Clark line is a major tectonic lineament that has undergone diverse and intermittent tectonism since its inception (Harrison and others, 1986). The northwest orientation of the maximum principal stress in this zone was indicated in a recent analysis of a minor earthquake located 15 km (9 miles) northeast of the Lucky Friday Mine (Sprenke and others, 1991).

Major faults in the Coeur d'Alene Mining District include the Osburn and the Dobson Pass. These two faults define the northeast portion of the district, including the Lucky Friday Mine (figure 2). These faults are generally believed to be some of the youngest features in the district (Hobbs and others, 1965).

There is general agreement that the most recent movement on the Osburn Fault is right lateral, indicating a northwest-trending tectonic stress field (Sprenke and others, 1991). There is less agreement on the direction of movement for the low-angle Dobson Pass Fault. Hobbs and others (1965) viewed the feature as a low-angle normal fault, primarily because younger strata form the hanging wall of the fault. White,[3] however, believes that the Dobson Pass Fault is a thrust fault, which would indicate significant east-west compression, at least north of the Osburn Fault. He cites numerous faults in the region with orientations similar to the Dobson Pass, many of which also have younger strata in their hanging walls (e.g., Harrison and others, 1986).

This study concentrates on understanding the stress state in the northeast portion of the Coeur d'Alene Mining District as defined by these features. Any relationship this stress state may have to the stress state in the remainder of the district is left as an open question.

[3]Personal communication from B. G. White, geologist, Spokane Research Center, USBM, 1994.

LUCKY FRIDAY MINE

Mining has followed the Lucky Friday vein down to the current depth, which is centered on the 5500 level approximately 1,675 m (5,500 ft) below the surface and 580 m (1,900 ft) below sea level. The vein ranges from several centimeters to 5 m (15 ft) thick and is nearly conformal in plan to an anticline plunging 60° to the southeast. Because the vein itself dips steeply (70° to 90°) to the south and east, it contacts progressively older rocks with depth (figure 3). The vein wall rock is the quartzitic Revett Formation.

Numerous faults and secondary folds are found in the mine, and some of these intersect the vein structure. Two prominent faults are the North and South Control Faults, which delineate the ends of the 460-m (1,500-ft) long Lucky Friday vein. The vein contains massive argentiferous galena and lesser amounts of sphalerite and tetrahedrite. The rock mass surrounding the vein at the current mining depth is the lower member of the Revett Formation of the Belt Supergroup. The lower Revett is made up of vitreous quartzite and sericitic quartzite beds from 30 to 90 cm (12 to 36 in) thick with soft interbeds of argillite generally less than 2.5 cm (1 in) thick. White has grouped these beds into 15- to 45-m (50- to 150-ft) thick subunits of predominantly hard, brittle, vitreous quartzite and relatively softer argillite and sericitic quartzite (figure 4).[4]

ANALYSIS OF SMALL-SCALE GEOLOGIC FEATURES

Small-scale geologic features at a number of sites in the Star and Lucky Friday Mines have been cited as evidence of current and historical principal stress orientations (Gresseth, 1964; Gresseth and Reid, 1968; Allen, 1979).

Gresseth (1964) used the orientation of rock fractures and joints to determine the direction of past and present ground forces on the 5900, 6100, and 6300 levels of the Star Mine. Gresseth classified sets of (1) extension joints,

[4]In a paper presented at the Belt Symposium III, August 14-21, 1993, Whitefish, MT, entitled "Geology of the Montanore Stratabound Cu-Ag Deposit, Lincoln and Sanders Counties, Montana," A. R. Adkins reported a similar identification of subunits in the lower Revett at the Montanore project in western Montana. Although both sets of subunits are identified by letters, this similarity is only coincidental. That is, subunit A may not contain the same strata at the respective mines despite their similar nomenclature.

(2) release joints, and (3) shear joints that indicated at least two periods of rock deformation. He identified the first of these as related to folding, with a predominantly horizontal, east-southeasterly, west-northwesterly direction of compression. He associated the most recent period of deformation as a north-south compression, roughly perpendicular to the vein, and probably caused by mining.

A subsequent report by Gresseth and Reid (1968) looked at a wider range of fabrics, from regional and macroscopic faults to quartz crystals and microfractures, on the 6500 and 6700 levels of the Star Mine. They concluded that during epochs of tectonic deformation, the maximum and minimum principal stresses were horizontally oriented and acted along northwest and northeast axes, respectively. They also concluded that the most recent tectonic deformation represents a rotation of the direction of minimum principal stress from horizontal to vertical. They observed good interscale correlation and statistical homogeneity of the tectonic fabric and interpreted this as indicating stress field homogeneity in this area during tectonic deformation.

Allen (1979) applied a similar approach to analyses of fractures and joints mapped on the 4250 level of the Lucky Friday Mine. He concluded that three different stress systems, with σ_1 oriented N 12° W, N 30° to 40° W, and N 30° to 40° E, most likely caused the joint and fold patterns. He chose the N 30° to 40° W stress system as being the latest on the basis of corroboration with his accompanying overcore stress measurement.

These early efforts at unravelling the tectonic history of the Coeur d'Alene Mining District were based on a vastly oversimplified view of the district's real structural complexity and tectonic history.[5] Subsequent work on tectonic history by White has drawn on a wide variety of geologic evidence to identify several periods of tectonic loading, with the latest evident tectonic period consistent with a northwest orientation of the maximum principal stress (Hobbs and others, 1965).

ROCK MASS RESPONSE TO MINING

ROCK MASS BEHAVIOR

Observations and measurements of rock mass behavior in an operating mine often provide valuable clues to the stress state and differences in the stress state in different parts of the mine. Rock mass behavior in the Coeur d'Alene Mining District, both inside and outside the study region, has been generally, but not entirely, consistent with a northwest trend for the maximum horizontal secondary principal stress (σ_{h1}). For example, Board and Beus (1989) measured rock deformation and loading of the concrete lining in the Lucky Friday Mine's Silver shaft and concluded that these measurements supported a N 45° to 65° W trend of σ_{h1}. In a more recent project, Pariseau and others (1992) concluded that rock deformation and local ground control problems in an experimental stope on the 5100 level supported a N 40° W trend for σ_{h1}.

Historical experience with rock bursts at the Lucky Friday Mine indicates that lithology exerts significant control on rock bursting. Blake and Cuvelier (1992) describe the evolution of rock-burst problems as different major lithologic units were encountered.

> During the 1960's, pillar bursts accompanying mining . . . within the upper Revett quartzite were the major ground control problem encountered at the Lucky Friday Mine . . . Bursting problems decreased during the 1970's as overhand cut and fill mining progressed through the softer and more argillaceous middle Revett . . . During the early 1980's, mining activity progressed into the harder and more-brittle quartzite within the lower Revett formation. The bursting frequency dramatically increased.

Blake and Cuvelier do not speculate whether the changes in rock bursting resulted primarily from a change in rock properties, or stress intensity, or a combination of these effects.

RAISE BORE BREAKOUTS

Observations of the deformation of bored raises are especially useful for estimating stress direction because of their size and vertical extent. Rock fracturing (breakouts) in these raises consistently occurs on the sides that parallel the orientation of σ_{h1} in a plane perpendicular to the raise. The short axis of the elliptical cross section created by this fracturing parallels the direction of maximum stress.

Breakouts and their relationship to principal stresses have been studied extensively. A recent report by the National Research Council (1993) provides a good review of the breakout phenomenon. The variety of orientations of these breakouts to local structure suggests that the breakouts are determined primarily by stress, as opposed to being determined by preexisting geologic structures. Several observations of borehole breakouts from active areas of the Lucky Friday Mine are discussed in the remainder of this section.

[5]Personal communication from B. G. White, geologist, Spokane Research Center, USBM, 1994.

Alimak Raise (3050 to 4250 Levels)

The 2.1-m (7-ft) diam "Alimak raise" was bored in the late 1970's from the 3050 to the 4250 levels. It passed from the upper levels in the shadow of mining to the deeper, unmined levels of the mine. The final shape of the cross section and bed orientation was measured at seven elevations by one of the authors (Blake). The lower three cross sections were least affected by mining-induced stress. These cross sections and a schematic showing contemporary mining progress are shown in figure 5.

The authors have estimated the locations of these sections with respect to locally defined lithologic subunits of the lower Revett Formation. Section 1 is believed to be in the middle Revett, section 3 is in a hard subunit (A) of the lower Revett, and section 2 is somewhere near the boundary between the middle and lower Revett.

The long axis of the ellipse created by the breakouts is roughly parallel to the strike of bedding in these cases. This observation is significant because it contradicts most experience in the district. That is, ground control problems are generally concentrated where bedding is parallel to the opening (Whyatt, 1986; Whyatt and Beus, 1987). Thus, the shape of the borehole breakout appears to be controlled primarily by stress, not structure. However, the breakouts do rotate with rotation of bedding strike. The appendix lists the orientation of bedding with respect to all borehole breakouts.

Silver Shaft Raise Bore

Surveys were also made of raise bores developed for use as ore passes and service raises in conjunction with underhand cut-and-fill stopes developed below the 5100 level (figure 6). Raises were developed as part of the Silver shaft loading pocket system in 1983 at the 5100 level, and breakouts provide evidence of stress orientation at some distance from the vein (figure 7). On the 5100 level, both raise bores broke out into ellipses during excavation, showing a northwest-trending σ_{h1}. Later observations on the 4900 and 5500 levels found elliptical cross sections of similar orientation. Thus, the orientation of σ_{h1} appears to be consistently northwest in subunits E through H at this location (figure 8).

106 and 107 Raise Bores

The 107 raise was drilled during 1985 in the northeast portion of the mine from the 5300 to the 5100 level. On the 5100 level, the 107 raise broke out from an initial 1.5-m (5-ft) diam circle to a 4.6- by 9.1-m (15- by 30-ft) ellipse with the long axis oriented to the northeast, indicating a N 45° W trend for σ_{h1} (figure 9). Breakouts on the 5160-access, 5210-sublevel, and 5300-level horizons of the raise indicated σ_{h1} orientations of N 40° W, N 35° W, and N 55° W, respectively. Subsequent development of the 106 raise between the 4900 and 5100 levels during late 1988 was accomplished without breakouts. Underhand mining during 1988 (see figure 9) was concentrated below the 5100 level.

97 Raise Bore

The 97 raise bore was developed about 64 m (200 ft) west of the 5300-level overcore measurement site. The observed breakout suggested a trend of N 55° W for σ_{h1} on the 5300 level (figure 10). In this case, the ellipse was oriented parallel to bedding.

Service Raise Bore

The service raise was developed from the 5400 level to the 5480 sublevel using the Swedish blasthole method. The ring of 14-cm (5.5-in) blastholes showed a consistent N 74° W orientation of σ_{h1} on the 5400 level. Further development of the raise to the 5560 sublevel was accomplished with a 1.2-m (4-ft) diam raise bore. This section of the raise was observed to break out to a northeast-southwest elongated ellipse showing a N 35° to 45° W trend of σ_{h1} on the 5480 sublevel. This raise was then slabbed out to a diameter of 2.4 m (8 ft). A section through the raise showed a transition from the hard G subunit on the 5400 level to the soft H unit on the 5480 sublevel (figure 11).

Grouse Vein Raise Bore, Star Mine

A raise bored on the 7300 level of the Star Mine at a stress measurement site broke out to indicate σ_{h1} oriented N 30° to 40° W. The raise and the stress measurement site are located in vitreous quartzite strata of the Revett Formation. This breakout (figure 12) was minor compared to many observed in the Lucky Friday Mine.

MINE STRESS FIELD CHARACTERIZATION

The objective of this work, characterization of the in situ stress field at the Lucky Friday Mine, has been addressed before (Beus and Chan, 1980; Whyatt, 1986). These studies assumed that the stress field was homogeneous, varied linearly with depth, and did not vary laterally. Some of the in situ stress evidence gathered in this study, most notably the overcore measurement from the 5300 level, is at odds with this assumption. Thus, characterization of the mine in situ stress field must start with examination of stress field variability.

DISTRIBUTION OF HORIZONTAL STRESS DIRECTION

The most common stress field characteristic obtained in this study was the orientation of σ_{h1}. The best information on maximum and minimum horizontal principal stress (σ_{h1} and σ_{h2}, respectively) magnitudes and orientation was provided by overcore measurements (table 3). These results, however, do not provide a consistent picture. While the orientations of the LF 4250 and Star 7300 measurements are similar, a major rotation in orientation of σ_{h1} was measured at the LF 5300 site. The spatial extent of this rotation can be examined using stress directions indicated by borehole breakouts, summarized in tables 4 and 5.

The frequency of these various orientations were plotted in 15° segments on a rose diagram (figure 13). Orientations of σ_{h1} are clearly distributed around a northwest-centered arc. Two of the overcore measurements lie in this central arc as well, with the LF 5300 measurement showing the only orientation outside the northwest quadrant.

The locations of σ_{h1} measurements from the 5100 through the 5700 levels are plotted on a map of the 5300 level by soft and hard lithologic subunits in figures 14 and 15, respectively. Breakouts in softer subunits are uniformly oriented and show a northwest orientation of σ_{h1}. Breakouts and stress measurements in the harder subunits also indicate a northwest orientation of σ_{h1}, except for breakouts at the 5400 level of the service raise and the LF 5300 measurement. Both sites are adjacent to the 38/Offset Fault. These stress rotations must be local as they are not reflected by most of the stress evidence. They imply that localized left-lateral shear stresses exist on the adjacent 38/Offset Fault, which has an apparent left-lateral offset. The Alimak raise breakouts in sections 2 and 3 suggest a similar mechanism.

Localized locking up of the fault would create the observed concentrations of shear stress. Locking up could occur where hard subunits come into contact across the fault, which is the case at both sites of rotated stress. The degree of rotation is greatest at the LF 5300 site, where the area of contact is smallest and the shear stress would be expected to be most concentrated. Physically, the

Table 3.—σ_{h1} and σ_{h2} calculated from overcore measurements

Site	σ_{h1}			σ_{h2}		
	MPa	psi	Bearing	MPa	psi	Bearing
LF 4250 level	89	12,900	N 38° W	49	7,100	N 52° E
LF 5300 level	114	16,500	S 80° W	73	10,600	N 10° W
Star 7300 level	53	7,700	N 39° W	35	5,100	N 51° E

Table 4.—General indications of σ_{h1} orientation

Location	Source	Orientation of σ_{h1}	Reference
Coeur d'Alene Mining District	Recent tectonic activity	Northwest	Hobbs and others (1965).
Star 5900 to 6300 levels	Rock fractures, joints	West-northwest	Gresseth (1964).
Star 6500 and 6700 levels	Geologic fabrics	Northwest	Gresseth and Reid (1968).
LF 4250 level	Rock fractures, joints	N 30°-40° W	Allen (1979).

Table 5.—Specific indicators of σ_{h1} orientation

Location and level	Bearing	Notes
Alimak raise:		
3980	N 40° W	
4020	N 65° W	
4100	N 75° W	
Silver shaft loading pocket:		
4900	N 45° W	Subunit E, hard.
5100	N 45° W	Subunit G, hard.
5500	N 45° W	Subunit G, hard.
Ore passes:		
5100-97	N 55° W	
5100-107	N 45° W	
5160-107	N 40° W	
5210-107	N 35° W	
5300-107	N 55° W	
Service raise, 5480	N 35°-45° W	
Blastholes, service raise, 5400	N 74° W	Diameter = 14 cm (5.5 in).
Grouse vein raise, Star Mine	N 30°-40° W	

strong, clay-poor, hard subunits could be expected to produce a higher resistance to slip along the fault than areas with relatively clay-rich wall rocks. Geologic information in the vicinity of the Alimak raise is insufficient to investigate whether this mechanism might explain the rotations of σ_{h1} in sections 2 and 3. This possibility requires further study, but for the purposes of this report, it is sufficient to recognize that observed horizontal stress rotations are a small-scale phenomenon relative to the scale of the mine and should be disregarded in developing estimates of average mine-wide stress conditions.

DISTRIBUTION OF STRESS COMPONENT MAGNITUDES

Evaluation of the variability of stress magnitudes must, by economic necessity, rely on relatively few overcore measurements. Resolving overcore stress estimates into vertical and map direction coordinates (table 2) provides a way to compare measurements with average overburden stress. While the estimates of vertical stress (σ_v) from the LF 4250 and Star 7300 measurements approximate the pressure expected from overburden loading [approximately 35 and 60 MPa (5,000 and 8,600 psi), respectively] (Beus and Chan, 1980), the vertical stress measured at the LF 5300 measurement site is clearly greater than expected [approximately 43 MPa (6,300 psi)]. Also, while this is the deepest site in terms of absolute elevation, the location of the Star Mine within mountains northwest of the Lucky Friday Mine (figure 16) makes the Star Mine deepest in terms of overburden.

At these depths, the effects of local topography are spread over a large area. Thus, the average elevation of the surface in the vicinity of the mine, not just depth below the immediate surface, becomes important. For this reason, the overburden loading calculation overestimates σ_v for the Star Mine and underestimates σ_v for the Lucky Friday Mine. A numerical model of overburden loading for a north-south vertical section was constructed to account for this influence. The results (table 2) closed about half the gap between measured and calculated σ_v for the Star 7300 and LF 4250 measurement sites. The σ_v at LF 5300, on the other hand, cannot be reconciled by topographic influence. The high σ_v at this location evidently reflects some local perturbation in the distribution of stress. Thus, overburden loading can account for the σ_v measured at two of the three sites.

The high σ_v measured at the LF 5300 measurement site may be related to the stress rotations near the 38/Offset Fault discussed earlier. On the other hand, a striking contrast in σ_v was apparent between hard and soft subunits at the LF 4250 measurement site (figure 17), although the overall measurement was dominated by readings from doorstopper cells installed in the relatively softer subunit. The absence of elevated σ_v in the hard quartzite at the Star 7300 measurement site departs from this pattern, but may reflect any number of other factors. The Lucky Friday overcore measurements indicate that steeply dipping hard subunits in the lower Revett carry at least 50 pct more σ_v than neighboring soft subunits. This effect appears to be widespread and is likely to be significant on a mine-wide scale.

Variations in other stress components, particularly the magnitude of horizontal stress parallel to bedding, are more problematic. The LF 4250-level measurement, for instance, while obtained using many redundant vertical overcore strain measurements, does not include a measurement of horizontal overcore strain in the hard subunit parallel to bedding. Furthermore, the concentration of shear stress required to generate the principal stress direction rotation noted at the LF 5300 site clouds examination of larger scale variations.

However, normal stress components oriented parallel and perpendicular to the 38/Offset Fault should not be greatly affected by this stress concentration and should provide some indication of whether other horizontal stress variations are present. Comparison of these stress components from the three overcore sites (table 6) shows remarkable agreement among the Lucky Friday measurements of the horizontal stress component that lies parallel to the 38/Offset Fault. Normal and traction stresses on the fault are dramatically different, however, and show a different sense of shear traction. Moreover, there is a definite concentration of horizontal stress oriented normal to the fault, suggesting concentrated horizontal stress at least across hard subunit contacts. Shear traction at the

Table 6.—Components of stress measurements with respect to orientation of 38/Offset Fault[1]

Measurement site	Subunit	Parallel		Perpendicular		Shear[2]	
		MPa	psi	MPa	psi	MPa	psi
LF 5300 level	Vitreous quartzite (hard)	91.2	13,230	95.6	13,870	-21.0	-3,040
LF 4250 level	Mainly sericitic quartzite (soft)	85.5	12,400	52.0	7,540	9.7	1,400
Star 7300 level	Vitreous quartzite (hard)	52.3	7,580	36.0	5,220	4.3	630

[1]Orientation of 38/Offset Fault is approximately N 53° W.
[2]Shear component is positive right-lateral.

5300 level is at a maximum at this orientation. Shear traction components at the 4250 level in the Lucky Friday Mine and the 7300 level in the Star Mine peak for a plane oriented N 80° W. The peak shear stress for the LF 4250 measurement is comparable to the LF 5300 measurement, but the peak stress for the Star 7300 measurement is less than half the Lucky Friday values. The Star measurement follows the pattern set by the LF 4250 measurement, but at a greatly reduced magnitude all around.

Thus, widespread variations can be expected in σ_v magnitudes, depending on lithology. Large, but spatially more limited, variations in normal and shear stress components relative to the 38/Offset Fault can be expected in the immediate vicinity of the faults. However, the magnitude of the horizontal stress component parallel to the 38/Offset Fault is remarkably stable, although all stress magnitudes are larger than those measured at the adjacent Star Mine.

STRESS ESTIMATE

After eliminating stress measurements and indicators that reflect localized stress variations, estimates of the overall stress field at the Lucky Friday Mine must be accomplished primarily with the same information available to previous studies, although overcore stress estimates have been refined. The exception is the widespread confirmation of the northwest orientation of σ_{h1} provided by raise bore breakouts. The localized nature of the stress field at the LF 5300 measurement site and the generally reduced magnitudes at the Star 7300 measurement site suggest that the best overall estimate will rely heavily on the LF 4250 measurement as representative of the mine stress field. Linear variation of stress with depth, with an unstressed surface and no lateral variations in stress, will be assumed in line with previous studies. The stress gradients and principal stress orientations that result from this procedure are presented in table 7.

Table 7.—Stress field estimate, Lucky Friday Mine

Stress component	Magnitude[1]		Bearing	Plunge
	kPa/m	psi/ft		
σ_{ns}	57	2.5		
σ_{ew}	49	2.2		
σ_v	35	1.6		
$\tau_{ns/ew}$	-15	-0.6		
$\tau_{ns/v}$	2	0.1		
$\tau_{ew/v}$	-10	-0.4		
σ_1	70	3.1	N 40° W	13°
σ_2	42	1.8	S 41° W	33°
σ_3	29	1.3	N 68° E	54°

[1]Magnitude is a function of overburden depth.

NOTE.—Empty cells in columns intentionally left blank.

DISCUSSION AND CONCLUSIONS

The availability of a new overcore stress measurement and successful reexamination of two earlier measurements from the same area promise to refine understanding of the in situ stress field in the vicinity of the Lucky Friday Mine. Although a northwest-trending σ_{h1} and overburden σ_v were generally indicated, and an average stress field proposed, there were significant local deviations as well. There seems to be a limited set of possibilities that would explain these deviations.

First, one or two estimates may be of poor quality or simply wrong. Errors in measurement, data screening, or data reduction could result in erratic estimates. However, the data screening and reduction procedures described in earlier parts of this series identified and removed a number of errors. The thorough review of field notes and reported procedures, as well as the careful screening of strain readings and an update of stress calculations, suggest that the stress estimates developed in this series of RI's are accurate. Also the general consistency of breakout results from a number of raise bore breakouts across the Lucky Friday Mine provides confirmation of the orientation of σ_{h1}.

Second, it is possible that the stress field estimates were correct, but that they did not represent the premining stress state because they had already been influenced by mining-induced stresses at the sites. Such effects at the two sites in the Lucky Friday Mine were calculated, assuming an elastic rock mass, and found to be negligible. There is a possibility that some inelastic mechanism may be able to increase the influence of mining on these sites to considerable levels. While impossible to disprove, it seems unlikely that the strong, localized variations in stress observed could be generated by mining.

Third, it is possible that all measurements are correct and that the premining in situ stress field in the vicinity of the Lucky Friday Mine includes significant local variations. This idea is not entirely new; for example, stress variations throughout the Coeur d'Alene Mining District have been suggested on the basis of differences observed in mining-induced seismicity throughout the district (Sprenke and others, 1991). Furthermore, this complexity would seem to exist at a number of scales, from individual beds to subunits to entire mines, prior to excavation. Finally, this complexity appears to be dependent on geologic structure and lithology.

This conclusion has important implications for research on rock-burst activity at mines throughout the Coeur d'Alene Mining District. This is especially true west of the axis of the Hook anticline in the Lucky Friday Mine, where concentrated rock-burst activity was noted in development openings, including the crosscut used for the LF 5300 measurement. If the extent and severity of this and other natural concentrations of stress can be estimated, the relative severity of rock-burst hazards may be anticipated, especially in development openings unaffected by mining-induced stress.

Additional research is needed to develop this capability. While hypotheses for concentration of σ_v and rotation of horizontal principal stresses have been advanced, further research is needed to confirm and further define these mechanisms. The widespread variations in σ_v between subunits, in particular, should be evident in records of mining-induced seismicity. Furthermore, numerical models need to be developed to explore how stress variations may be expected to evolve with further mining in the Lucky Friday Mine and provide a guide to variations in stresses likely to be encountered by mining anywhere in the Revett Formation. Work on these topics is continuing as part of ongoing USBM investigations of methods to identify and reduce rock-burst hazards. Completion of this research will provide mine engineers with a tool to anticipate and reduce rock-burst hazards.

ACKNOWLEDGMENTS

Charles Fairhurst, professor, Department of Civil Engineering, University of Minnesota, Minneapolis, MN; Mark Board, manager of mining engineering, Itasca Consulting Group, Minneapolis, MN; and Mel Poad, group supervisor, Spokane Research Center, USBM, Spokane, WA, provided invaluable support and guidance during this study. The assistance provided by Brian White, geologist, Spokane Research Center, with geologic mapping and development of subunit classifications for the Lucky Friday Mine is gratefully acknowledged.

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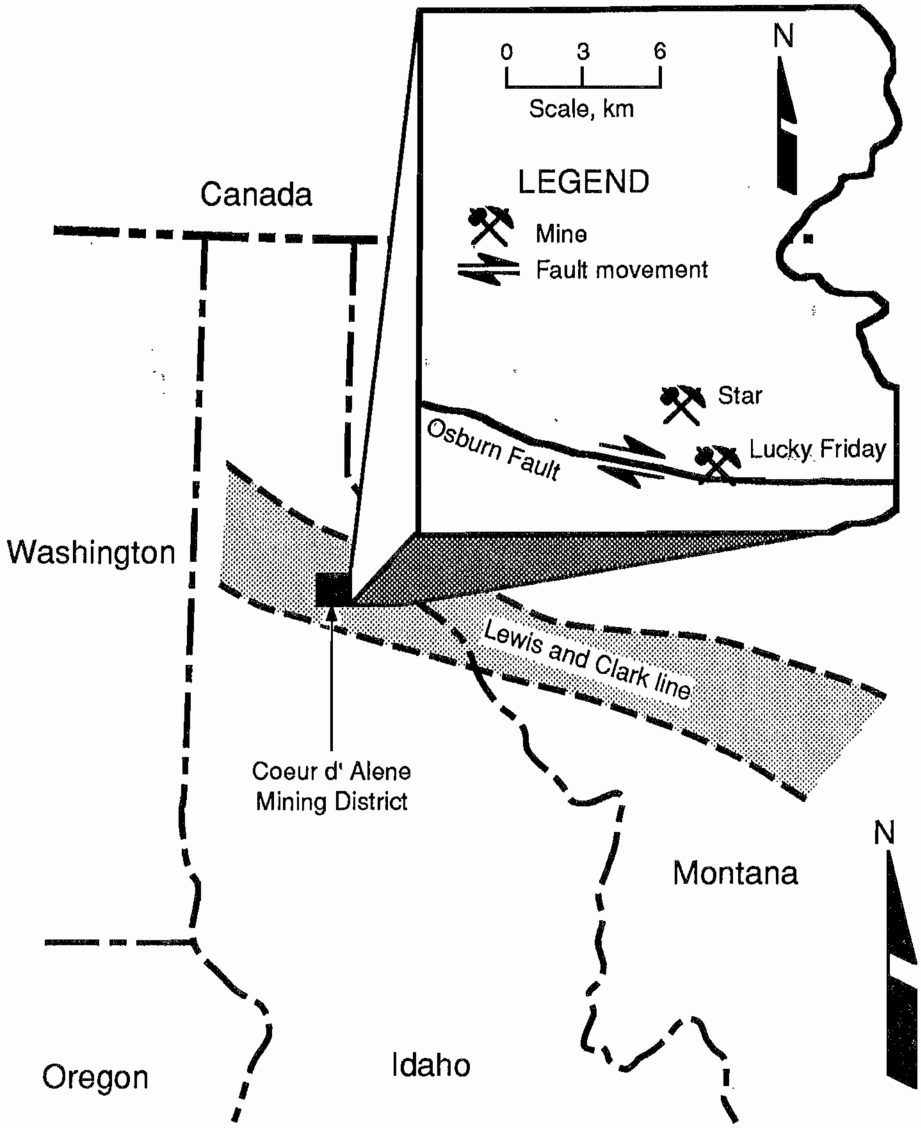
APPENDIX.—ANGLE BETWEEN LONG AXIS OF ELLIPSE AND BEDDING STRIKE

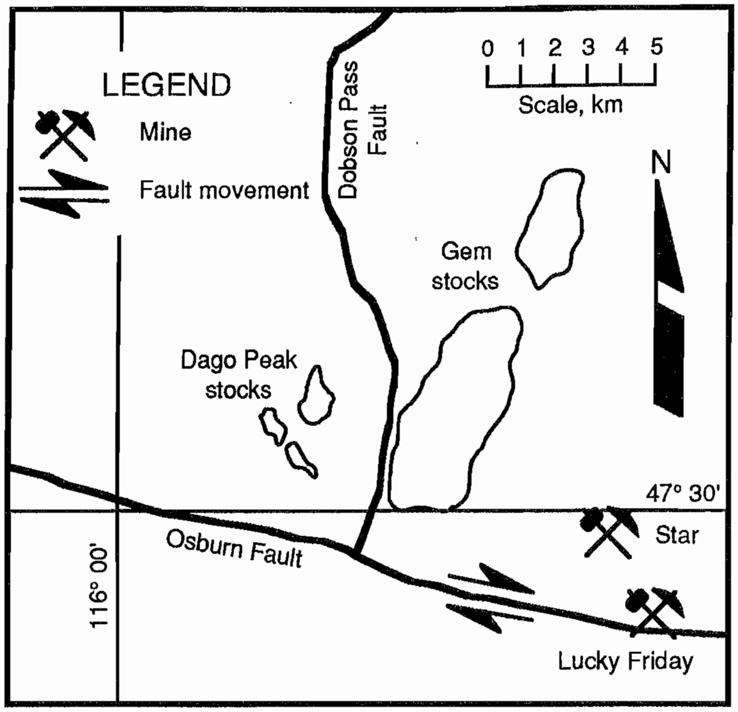
Location and level	*Angle*
Alimak raise:	
3980	0°
4020	40°
4100	20°
Silver shaft loading pocket:	
4900	0°
5100	45°
5500	45°
Ore passes:	
5100-97	45°
5100-107	45°
5160-107	45°
5210-107	0°
5300-107	55°
Service raise, 5480	35°-45°
Blastholes, service raise, 5400	74°
Grouse vein raise, Star Mine	80°-90°

Figure 1



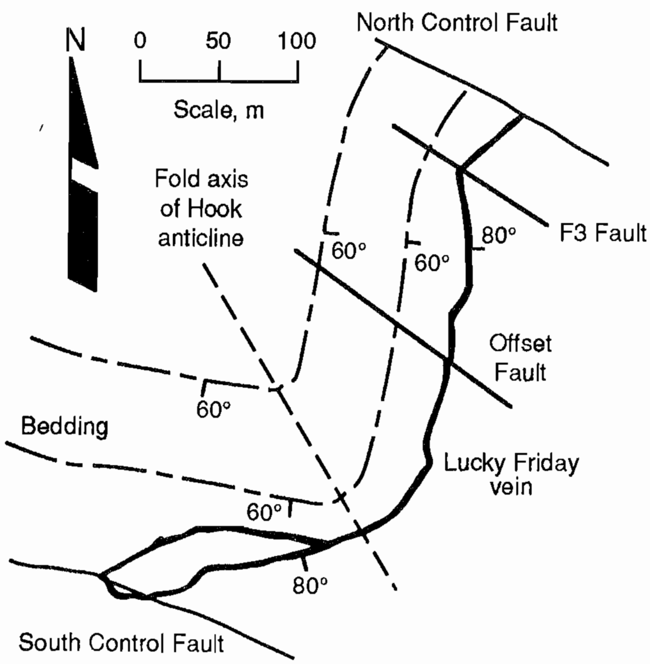
Location of Lucky Friday Mine in Coeur d'Alene Mining District of northern Idaho.

Figure 2



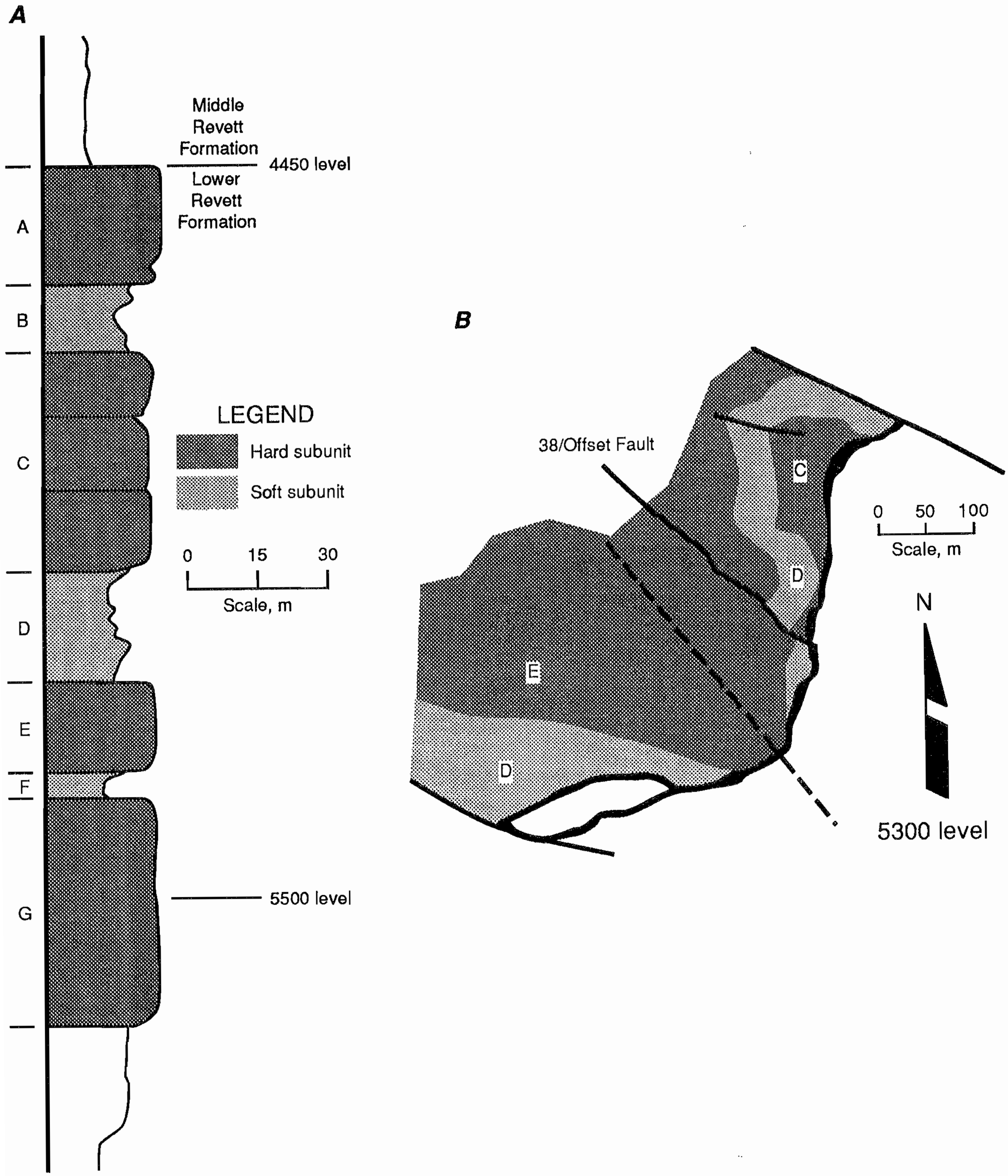
Major geologic features of Coeur d'Alene Mining District.

Figure 3



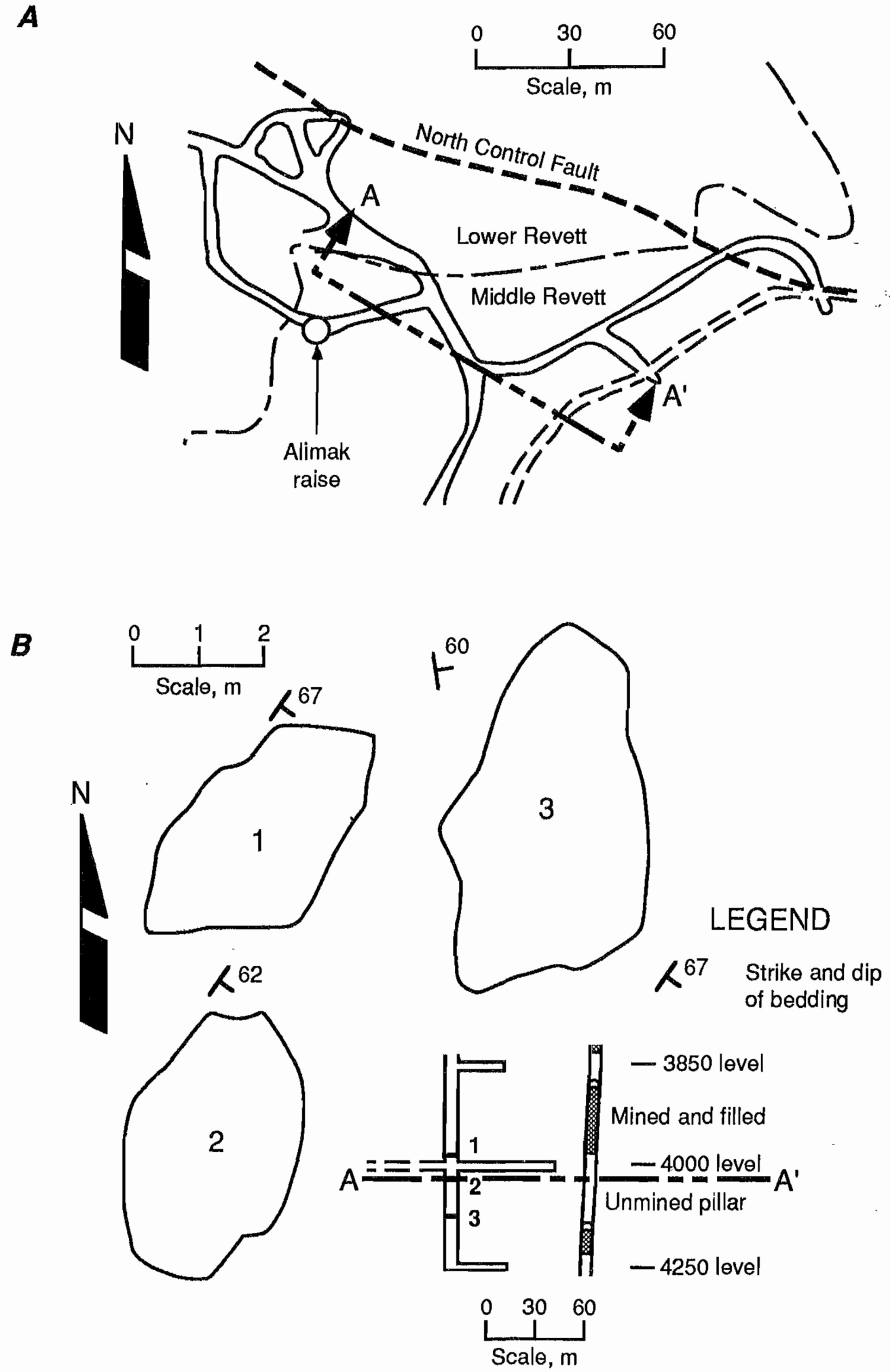
Major structural features of 5300 level, Lucky Friday Mine.

Figure 4



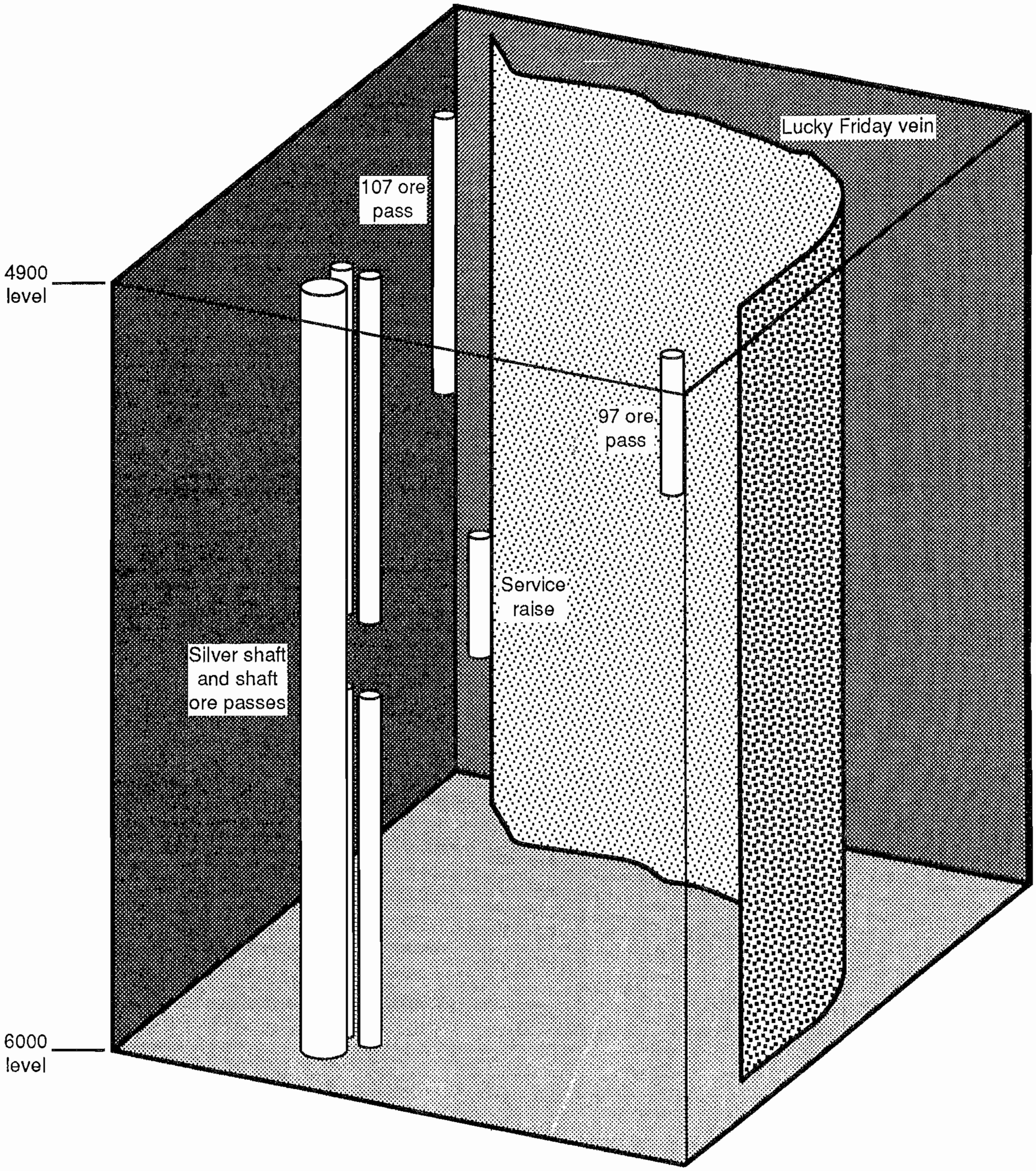
Lithologic subunits in lower Revett Formation A, Simplified geologic column; B, 5300 level, plan view. Dotted line indicates axial plane of Hook anticline.

Figure 5



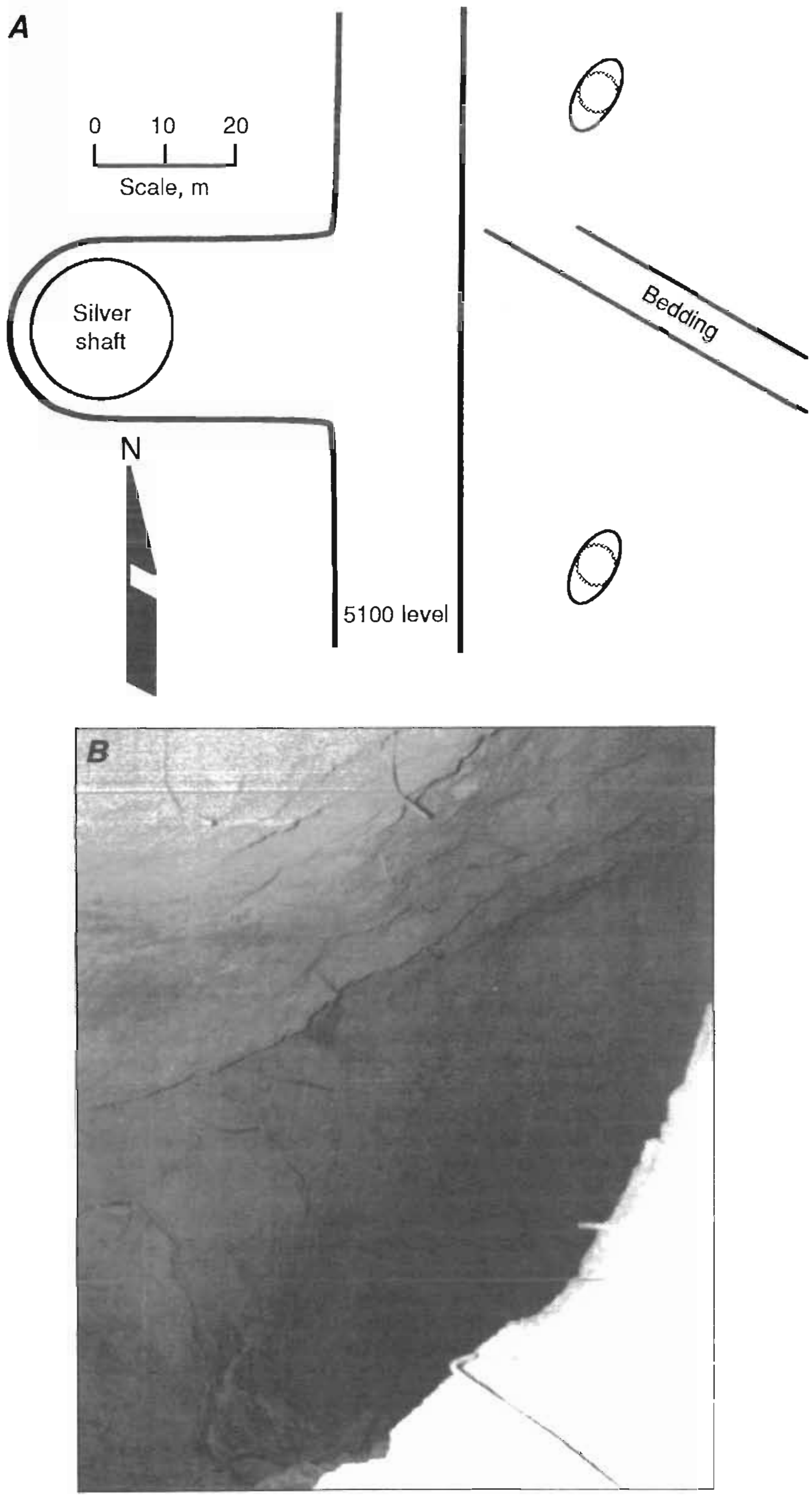
Alimak raise. A, Location of Alimak raise on 4250 level; B, vertical section showing mapped breakouts on sections 1, 2, and 3. Breakouts were interpreted to indicate orientation of σ_{h1}.

Figure 6



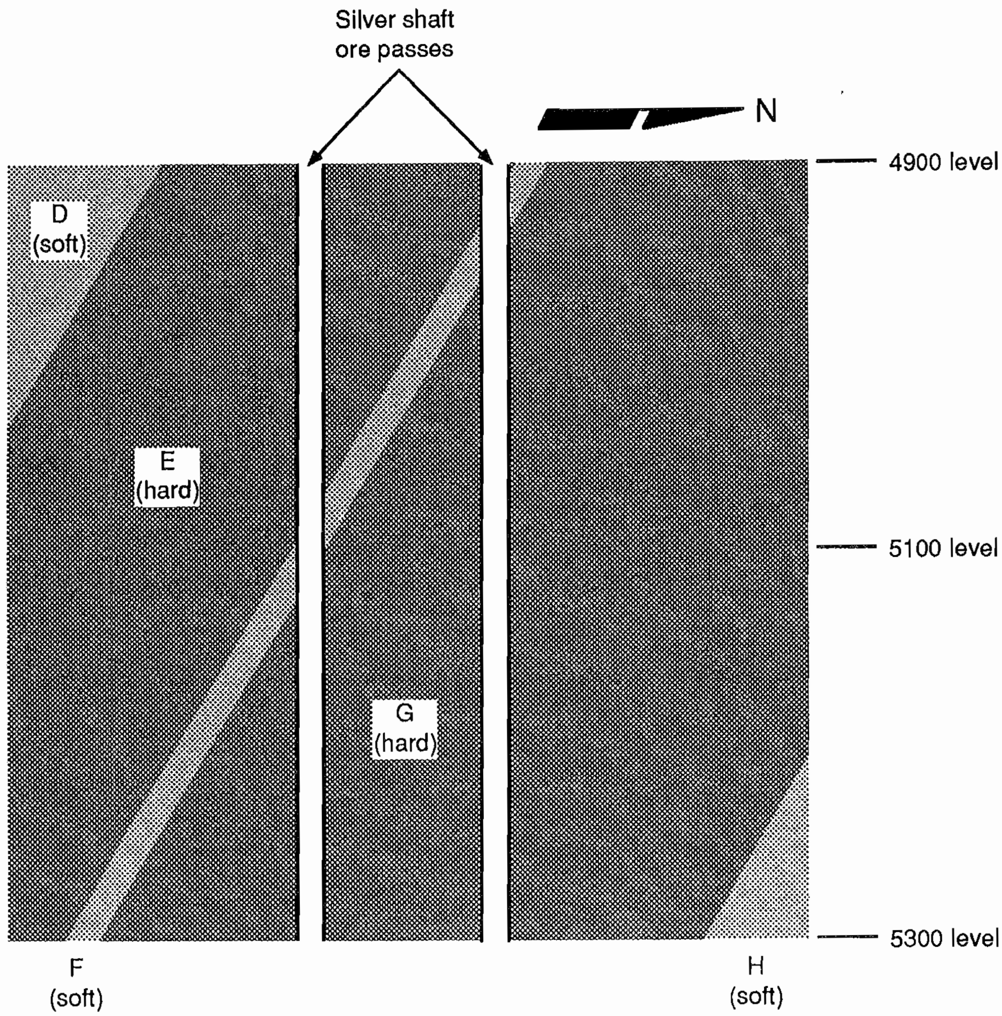
Silver shaft and system of circular ore passes and service raises developed to support longwall mining of vein.

Figure 7



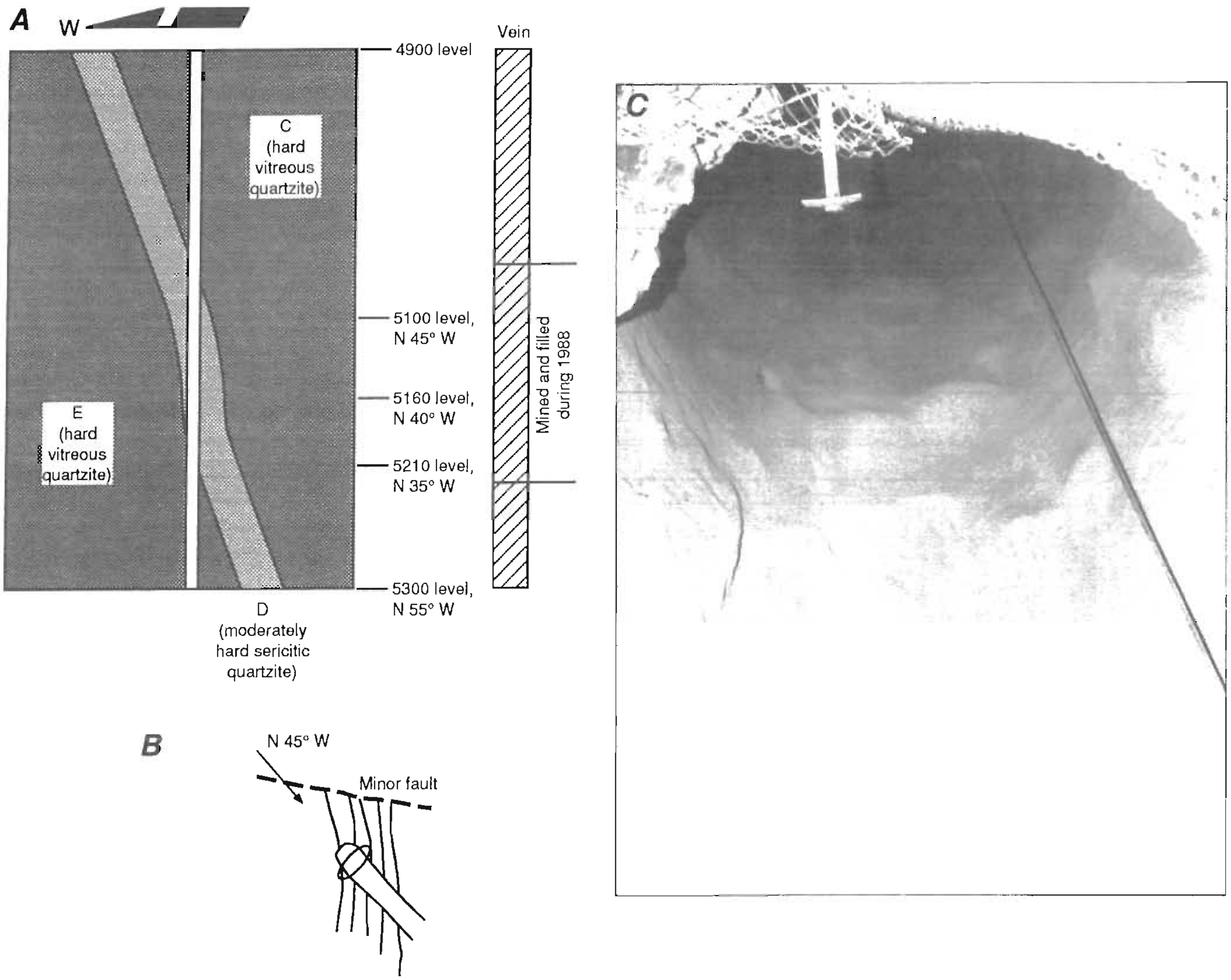
Breakouts observed in Silver shaft ore passes on 5100 level. A, Plan view. Circle (dotted line) indicates original shape of ore pass, while ellipse (solid line) indicates final shape after breakouts occurred. B, Breakout as observed looking down north ore pass.

Figure 8



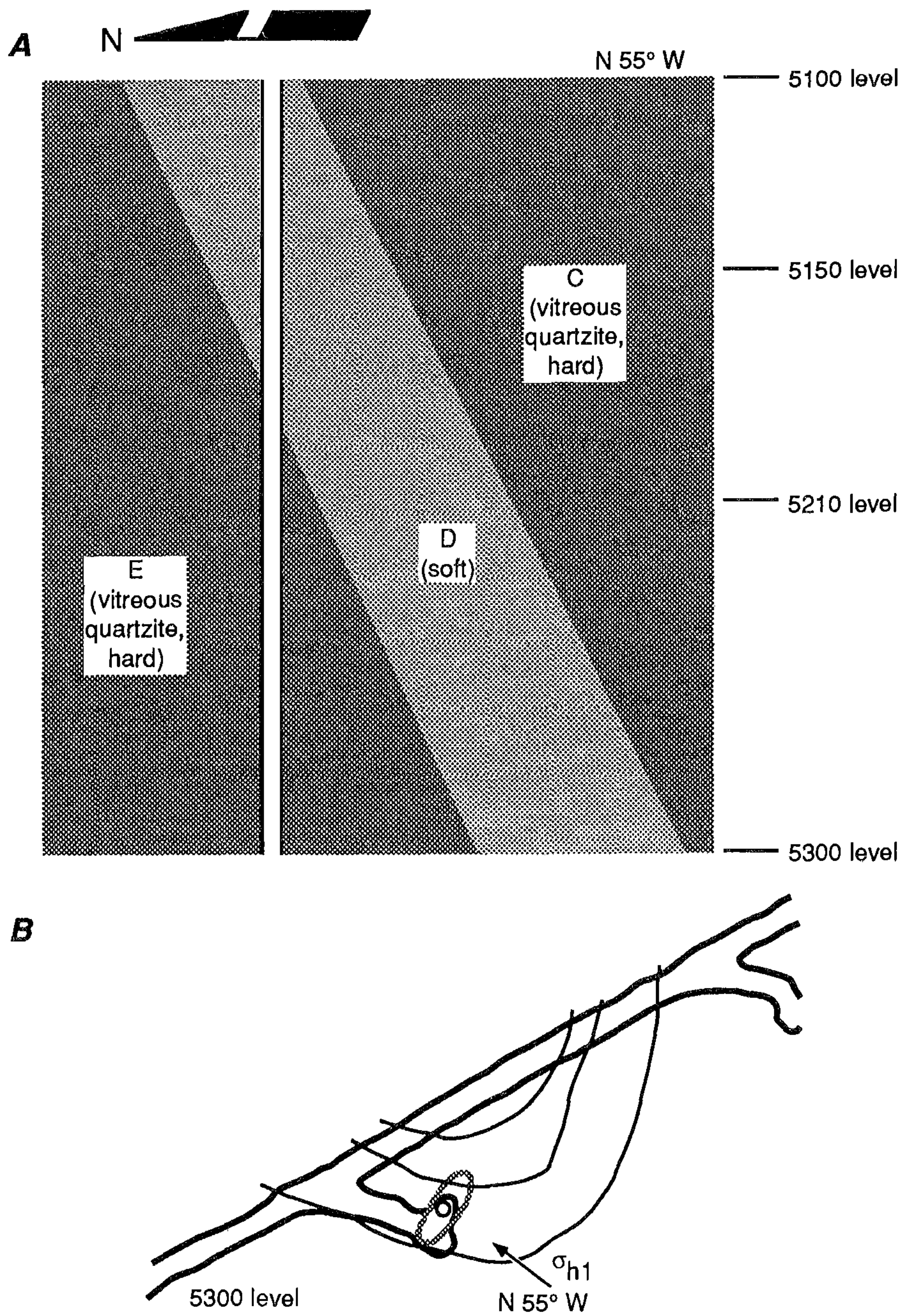
Subunit lithology of Silver shaft ore passes (4900 to 5300 levels).

Figure 9



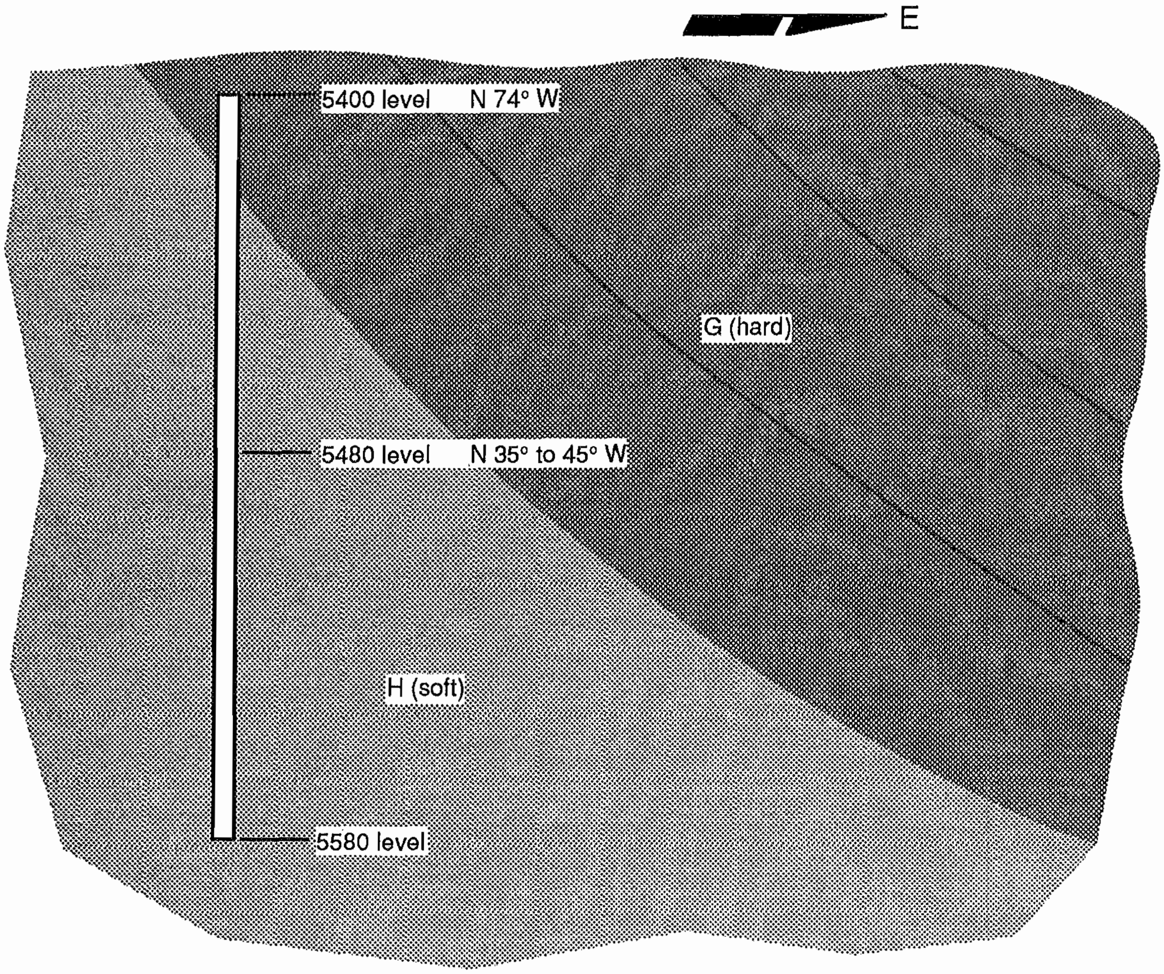
106 and 107 ore passes. A, Subunit lithology, breakout indicators of σ_{h1} orientation in 107 ore pass, and mining progress on nearby vein; B, geology and breakout in plan view, 5100 level; C, 5100-107 ore pass looking up 5160 access. Vein was unmined during development of 107, but some mining had been conducted before completion of 106.

Figure 10



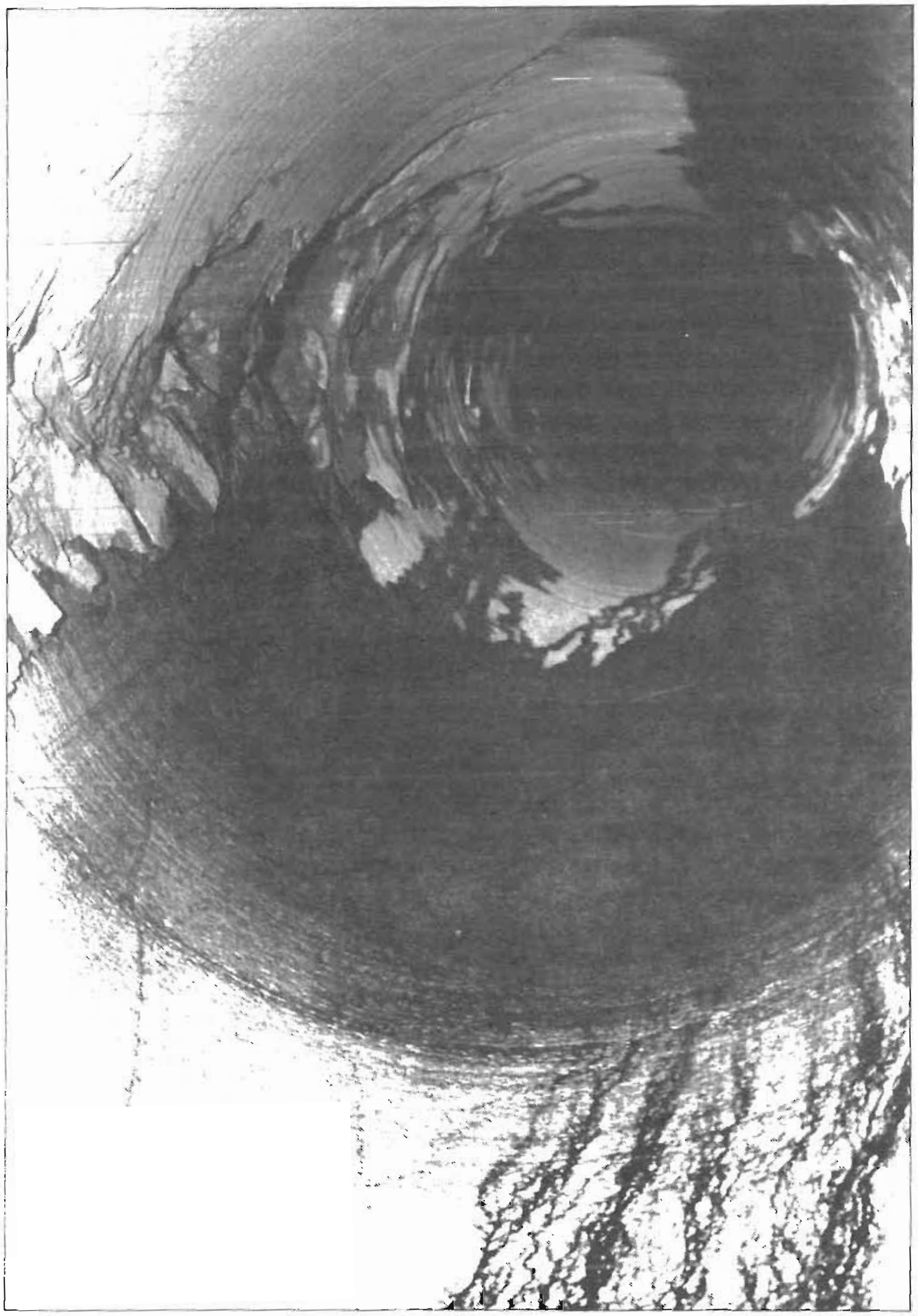
97 ore pass. A, Subunit lithology and breakout indicators of σ_{h1} orientation in 97 ore pass; B, geology and breakout in plan view, 5300 level.

Figure 11



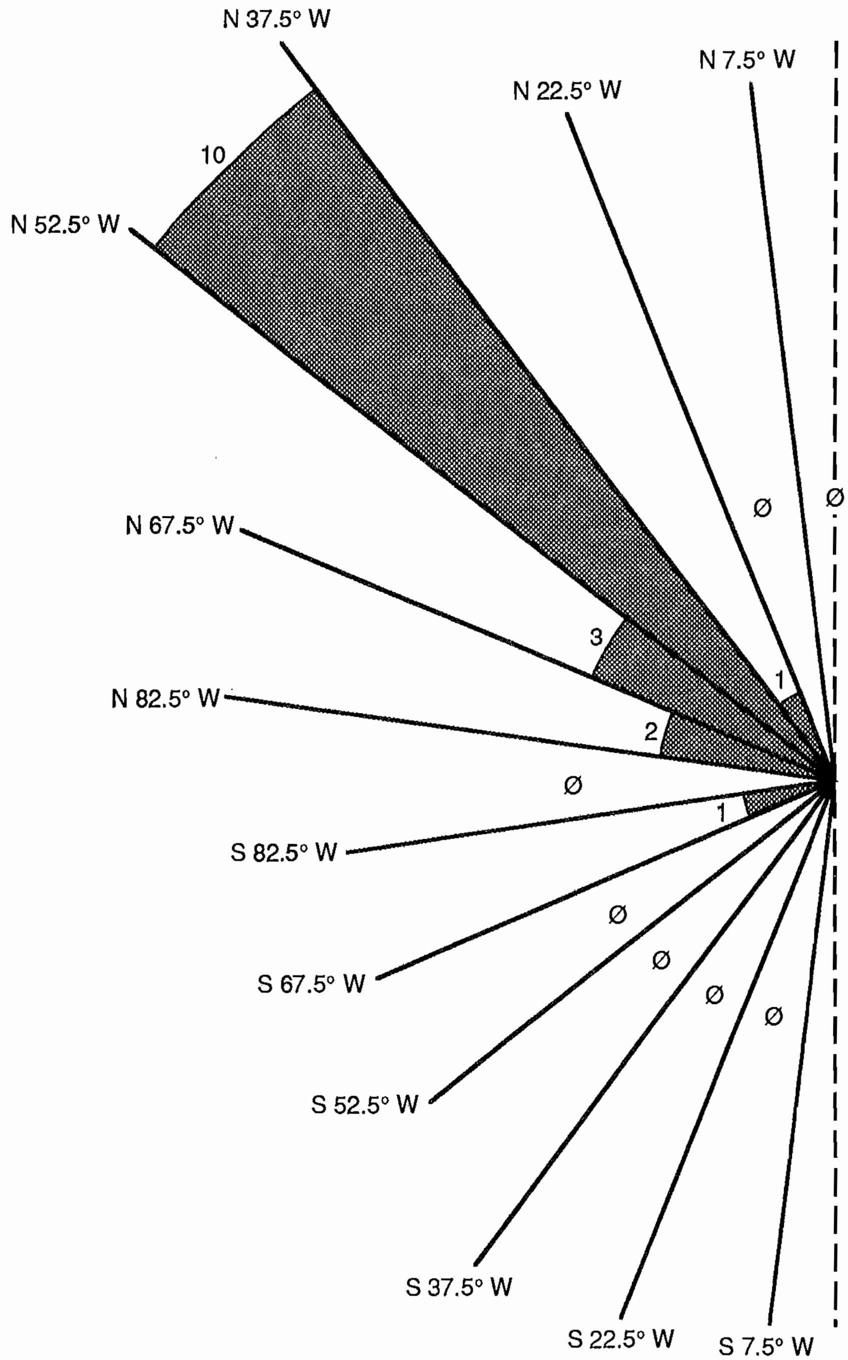
Subunit lithology and breakout indicators of σ_{h1} orientation in service raise.

Figure 12



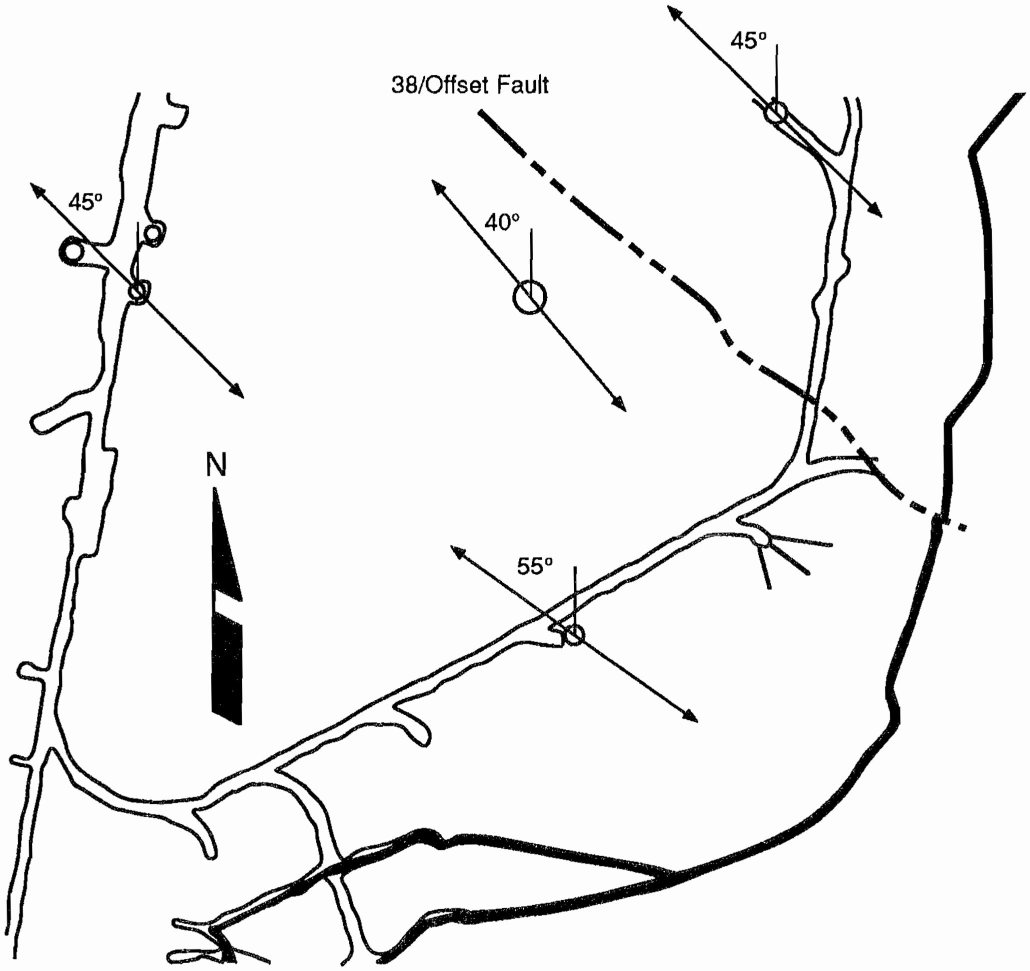
Raise bore breakouts, 7300 level, Star Mine.

Figure 13



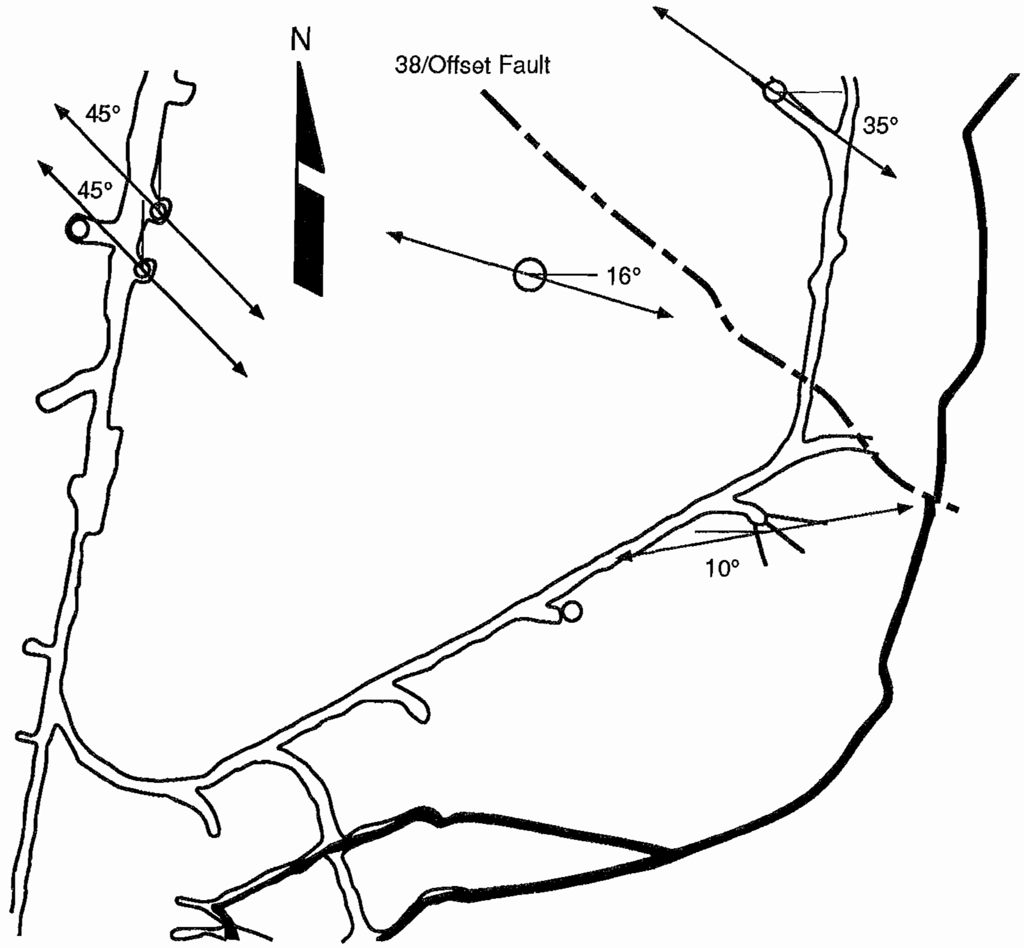
Rose diagram showing frequency of σ_{h1} orientation as indicated by overcore measurements and breakouts plotted in 15° intervals.

Figure 14



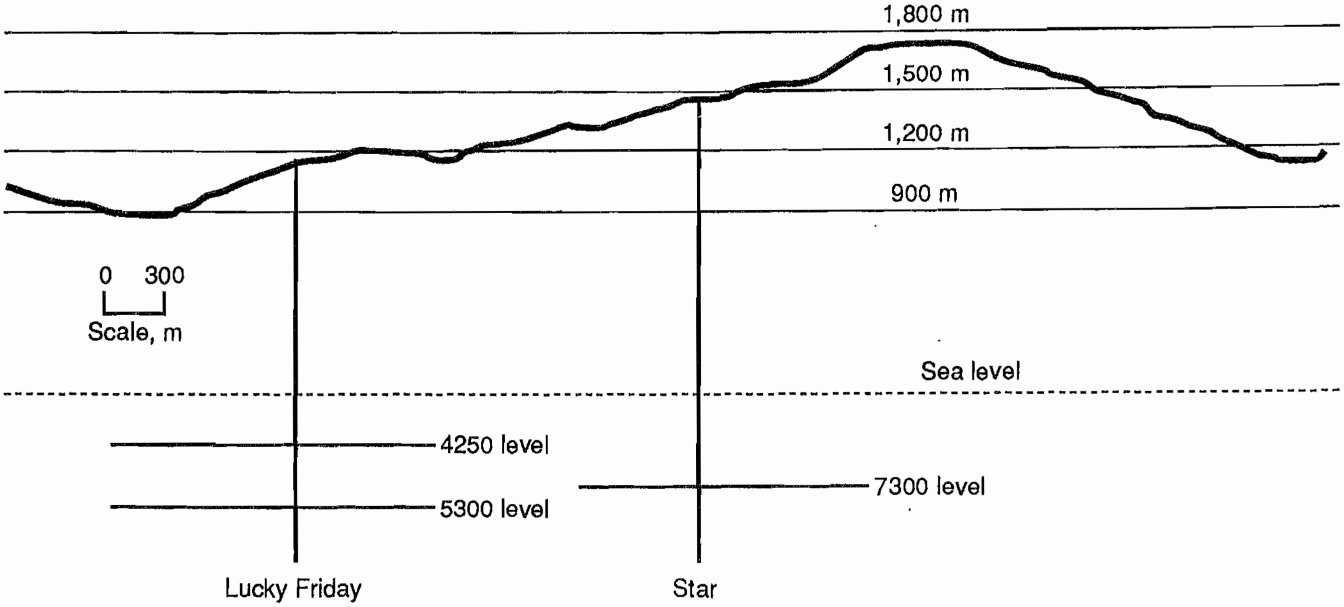
Location and subunit lithology of breakout indicators of σ_{h1} orientation in vicinity of LF 5300-level overcore measurement site in soft subunits.

Figure 15



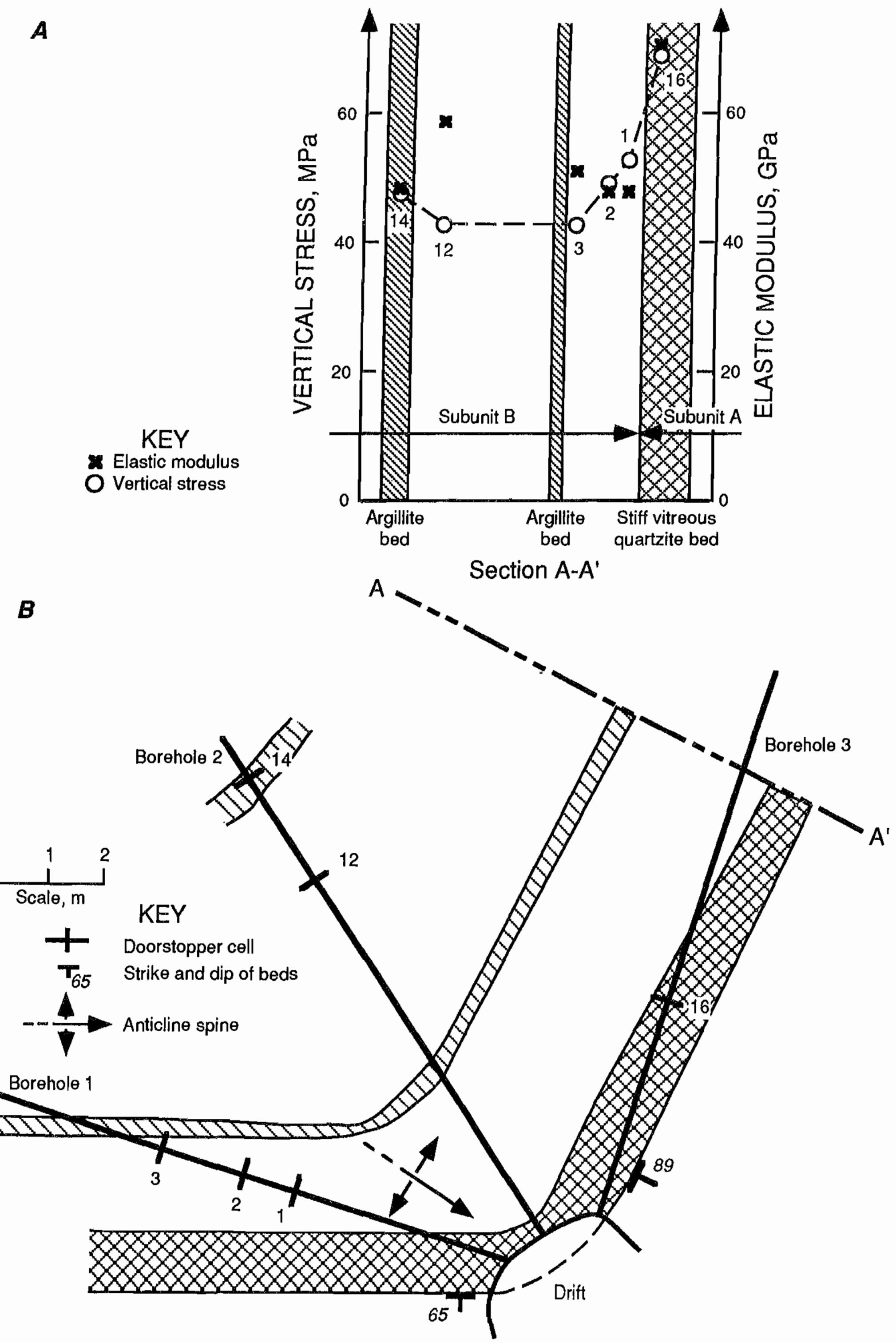
Location and subunit lithology of overcore and breakout indicators of σ_{h1} orientation in vicinity of LF 5300-level overcore measurement site in hard subunits.

Figure 16



Topography over north-south cross section through Lucky Friday and Star Mines.

Figure 17



Relationship among stratigraphy, rock elastic modulus, and estimated vertical in situ stress component at LF 4250 measurement site. Numbers indicate doorstopper cells. Both doorstopper cells and elastic modulus (heavy crosses) are plotted as to relative stratigraphic position. Note that elastic modulus is read as gigapascals, while σ_v is read as megapascals. A, Variations in vertical in situ stress component by stratigraphic location; B, plan view of measurement site.

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